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Estimation of Metallic Structure Durability for a Known Law of Stress Variation

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Abstract. Overload of machines working in transient operational modes leads to such stresses in their bearing metallic structures that considerably exceed the endurance limit. The estimation of fatigue damages based on linear summation offers a more accurate prediction in terms of machine durability. The paper presents an alternative approach to the estimation of the factors of the cyclic degradation of a material. Free damped vibrations of the bridge girder of an overhead crane, which follow a known logarithmical decrement, are studied. It is shown that taking into account cyclic degradation substantially decreases the durability estimated for a product.

INTRODUCTION

Many transporting machines inevitably face once-in-a-while overloads of their metallic structures during operation. A peak overload causes free damped vibrations of a structure, and their number depends on the damping properties of the structure. If σ_0 is in effect an amplitude of maximal reduced stress at a potentially critical point of the structure under overloading, then the emergent vibrations are described by the known law [1]

$$\sigma = \sigma_0 e^{-rt}, \tag{1}$$

where r is the vibration damping coefficient, which is directly related to the logarithmical decrement $\delta = Tr$; T is the vibration period. The data on the vibration decrement could be either found in the reference sources, or obtained from calculations, or determined from experimental vibrorecords [1-3].

This paper presents a comparative analysis of two methods to evaluate the durability of a metallic structure under a peak overload. One is based on a linear hypothesis of fatigue damage summation. The other method – the one proposed by the authors of this paper – consists in studying the cyclic degradation of material properties, which was proved to be valid in calculations taken for several metallic structures [4, 5]. Those papers studied the case of block loading. In what follows, a case of cycle-to-cycle stress variation by a known law for free damped vibrations is considered. Only stresses exceeding the endurance limit σ_R are taken into account.

PREDICTING THE DURABILITY OF STRUCTURES BY LINEAR SUMMATION OF FATIGUE DAMAGES

A typical block of stress cycles for a one-time peak overload is shown in Fig. 1. Operational peak overloads could stem from various causes and therefore have different values of σ_0 and σ_R. However, since the conditions of experiments conducted for two methods are deemed to be invariable, those parameters are assumed to be constant.

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The diagram of stress variation in Fig. 1 is implemented, for example, in the bridge girder of an overhead crane when it drives into a damping device.

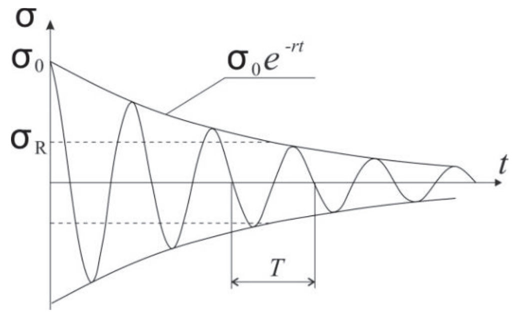

FIGURE 1. Free structural vibrations

The fatigue curve is supposed to take on a typical form,

$$\sigma_R^{\alpha} N_U = \sigma_i^{\alpha} N_i,$$

where N_U is basic durability, α is the structural material constant, σ_i is the stress amplitude for the *i*-th cycle in a block, N_i is corresponding durability from the fatigue curve. According to expression (1), we have

$$\sigma_i = \sigma_0 e^{-rTi} = \sigma_0 e^{-\delta i}, \tag{2}$$

$$N_i = N_U \left(\frac{\sigma_R}{\sigma_0 e^{-\delta i}} \right)^{\alpha}.$$

Fatigue damage caused by the stresses of one block can be determined using the linear hypothesis as

$$\omega_U = \sum_{i=1}^{k} \frac{1}{N_i} = \sum_{i=1}^{k} \frac{1}{N_U \left(\frac{\sigma_R}{\sigma_0 e^{-\delta i}} \right)^{\alpha}}, \tag{3}$$

where the number of cycles *k* in the consideration of Eq. (2) is determined on the condition that

$$\sigma_k = \sigma_0 e^{-rkT} = \sigma_R,$$

and this means that the number of cycles in a block is

$$k = -\frac{1}{\delta} ln \frac{\sigma_R}{\sigma_0}.$$

Next follows the estimation of structural durability defined in blocks ω_U^{-1} and in the number of cycles prior to failure

$$N_{LG} = \omega_U^{-1} k.$$

ESTIMATION OF STRUCTURAL DURABILITY SUBJECT TO CYCLIC DEGRADATION OF MATERIAL STRENGTH PROPERTIES

The durability of products predicted on the basis of the linear hypothesis (3) often substantially differs from the experimentally obtained one. The phenomenological approach proposed here is based on the analysis of relations between static and cyclic properties of structurally inhomogeneous materials [4]. This process is associated with the fatigue process, and corresponding kinetic curves are included in the model of material cyclic degradation [5].

In the force approach, the ultimate strength of a material $S_U(\sigma_M;\mathrm{n})$ is selected to be a controlling parameter, thus becoming a function of maximal stress for a steady-state cycle σ_M and the number of prior cycles. On the condition of best approximation for experimental data, an exponential function has been chosen,

$$S_U(\sigma_M;n) = S_{U0} - k_\sigma n^m, \tag{4}$$

where the expression $k_\sigma n^m$ has been taken in the form of the Corten-Dolan damaging function, which was experimentally verified. Then, k_σ is determined on the condition of failure

$$S_U(\sigma_M;N_M) = \sigma_M, \tag{5}$$

which has the meaning of a criterion for fatigue damage from steady-state loading, and the function (4) takes the form

$$S_U(\sigma_M;n) = S_{U0} - \frac{S_{U0}-\sigma_M}{N_M^m} n^m, \tag{6}$$

where N_M is durability from the Wöhler diagram, m is the experimental constant for a material.

Figure 2 provides a scheme for durability estimation of varied stresses.

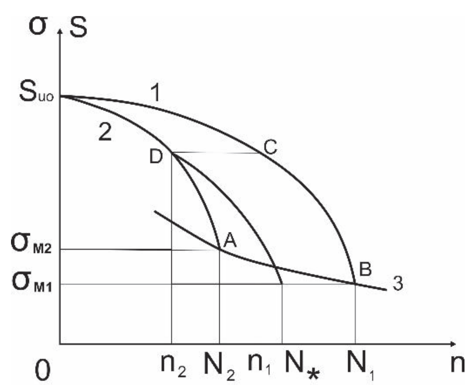

FIGURE 2. Durability for a single variation of cyclic stresses

Experimental curves 1 and 2 in Fig. 2 reflect a decrease in ultimate strength with an increase in the number of cycles. Line 3 is a Wöhler curve. Cycling at the level of stresses σ_{M2} during the n_2 number of cycles leads to material transition to the state *D*. We assume two cyclic material states *D* and *C*, obtained from different histories of loading, to be equivalent. Then, the equivalent number of cycles $n_E = n_1$ at the level of stresses σ_{M1} is determined from the obvious equation $S_U(\sigma_{M2},\mathrm{n}_2) = S_U(\sigma_{M1},n_1)$. With expression (6) taken into account, we have

$$n_E = n_2 \frac{N_{M1}}{N_{M2}} \left(\frac{S_{U0} - \sigma_{M2}}{S_{U0} - \sigma_{M1}} \right)^{1/m} .$$

The cycling continues at the level of stresses σ_{M1}, and resistance decreases following the path *CB* in accordance with formula (6).

The example shown in Fig. 2 has the durability N_* evaluated for a single variation of stresses as follows. Due to the continuity of the process, the sector *CB* is transferred to the left by the number of cycles determined by the sector *DC*. For the resultant durability N_*, we have

$$N_* = N_1 + n_2 \left[1 - \frac{N_1}{N_2} \left(\frac{S_{U0} - \sigma_{M2}}{S_{U0} - \sigma_{M1}} \right)^{1/m} \right] ,$$

which differs from the linear summation by the presence of the parenthesized multiplier, reflecting the effect of interaction of stresses of various levels.

When maximal stresses of a cycle change following the law (1), it leads to continuous variation of stresses for $\Delta n = 1$. To determine the durability of metallic structures, an algorithm for the evaluation of the current resistance is developed. The criterion of fatigue failure (5) is generalized for an arbitrary number of stress variations.

NUMERICAL ILLUSTRATION FOR EVALUATING THE DURABILITY OF THE BRIDGE GIRDER OF AN OVERHEAD CRANE UNDER OVERLOAD FROM BRAKING

Parameters of the bridge girder of a 20-ton overhead crane are evaluated using typical strength and rigidity calculations. Stresses from braking are determined by means of a dynamic motion model for a girder with a trolley and its load. Maximal normal stresses in the girder when the crane stops are σ_0 = 120 MPa, the ultimate strength of the structural material is S_{U0} = 470 MPa, the endurance limit for the structure with welded joints and basic durability of N_U = $2 \cdot 10^6$ cycles is σ_R = 50 MPa, the logarithmic decrement of vibrations for the metallic structure of the crane is assumed to be δ = 0.1 [3], and the fatigue curve factor for the St3sp5 steel is α = 5.34.

The results of the calculations which allow for material degradation and consider various values of the factor *m* are provided in Fig. 3. When the spectrum of loads contains peak overloads, the calculated durability is substantially below the one obtained from the linear summation of damages. This result qualitatively agrees with the known experimental data [4].

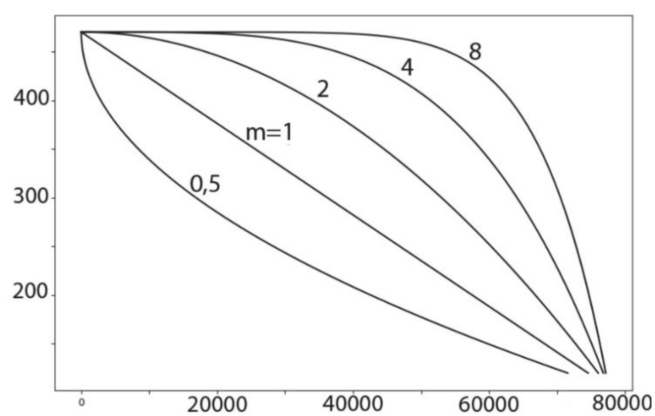

FIGURE 3. Decrease in strength at a critical point of the metallic structure for various values of the material constant *m* in formula (10)

The value of the kinetic curve degree (4) for the studied materials is close to two [4]. The number of blocks corresponding to the number of times the crane breaks prior to the emergence of a fatigue crack is 7,606 for $m = 2$. When the linear hypothesis is used, the crane is predicted to break by 70% more often, with the number of braking times equaling to 13,063.

It should be noted that, in the example provided here, the durability depends weakly on the form of the material strength degradation curve at a critical point of the structure. This stands in contrast to the current strength value, which may differ by an order of magnitude. The danger of once-in-a-while peak overloads rises with a decrease in the factor m for the kinetic curve of a material.

CONCLUSION

For a peak overload from bridge braking, the method of resistance functions gives a conservative prediction of girder durability in comparison with linear summation. Theoretically, concurrence with the linear prediction is possible for infinitely large values of the kinetic curve degree factor, i.e. when the properties of a material remain unchanged until a fatigue crack occurs. And it is where a certain physical meaning of linear summation seems to be contained. The obtained results allow us to proceed to a practically important case of loading with the amplitude and the asymmetry parameter varying from one cycle to another.

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